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REPORT DOCUMENTATION PAGE — Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Uncla[ssified]	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) LPS #90-17	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Laboratory of Plasma Studies Cornell University; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Plasma Physics Division Naval Research Laboratory
6c. ADDRESS (City, State, and ZIP Code) Ithaca, NY 14853	7b. ADDRESS (City, State, and ZIP Code) Washington, DC 20375-5000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Plasma Physics Division, NRL; 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20375-5000	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. —; PROJECT NO. N00014-89-J-2009; TASK NO. —; WORK UNIT ACCESSION NO. —

11. TITLE (Include Security Classification)
"Plasma Physics Applications to Intense Radiation Sources, Pulsed Power and Space Physics"

12. PERSONAL AUTHOR(S)
Hammer, David A.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 01/01/89 TO 12/31/89	1990 September 12	36

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Pulsed Power Applications, Soft X-ray laser
			Plasma Opening Switch
			Plasma Radiation Sources

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report presents the status of research tasks supported by funds from the Plasma Physics Division, Naval Research Laboratory (NRL) during calendar year 1989. Included are descriptions of results from experiments on the X-Pinch as a pump source for short wavelength photopumped lasers, long conduction time Plasma Opening Switch research, both experimental and theoretical, and a brief description of experiments initiated on the use of electro-optical diagnostics to study the plasma produced by NRL "flashboards" (commonly used in opening switch experiments). Keywords

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION
22a. NAME OF RESPONSIBLE INDIVIDUAL David A. Hammer	22b. TELEPHONE (Include Area Code) 607-255-4127; 22c. OFFICE SYMBOL

DD Form 1473, JUN 86 — Previous editions are obsolete. — SECURITY CLASSIFICATION OF THIS PAGE

90 09 17 012

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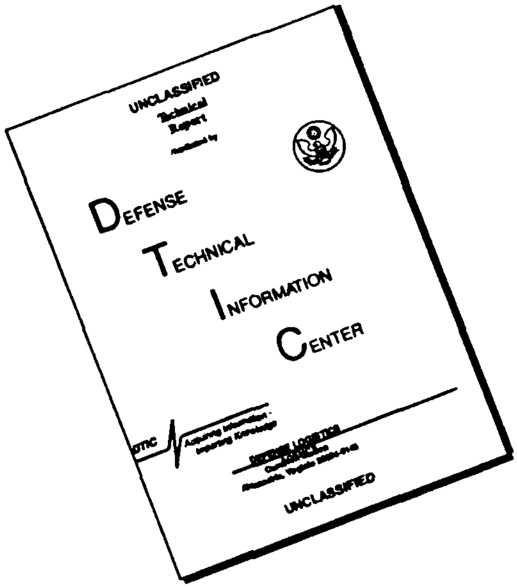

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PLASMA PHYSICS APPLICATIONS TO INTENSE RADIATION SOURCES, PULSED POWER AND SPACE PHYSICS

I. Introduction

This report presents the status of research tasks undertaken with the support of funds from the Plasma Physics Division, Naval Research Laboratory (NRL) under contract N00014-89-J-2009 during calendar year 1989. Included in this report is a description of results from experiments on the X-Pinch as a pump source for short wavelength photopumped lasers, long conduction time Plasma Opening Switch research, both experimental and theoretical, and a brief description of experiments initiated on the use of electro-optical diagnostics to study the plasma produced by NRL "flashboards" (commonly used in opening switch experiments). All of these tasks continued into calendar year 1990.

II. X-Pinch XUV and Soft X-Ray Radiation Sources for Pumping Short Wavelength Lasers

This research, carried out in collaboration with Dr. Jack Davis' branch at NRL, involves using multiple x-pinches formed by twisting two fine aluminum wires so that they touch at regular intervals as the load for our 0.5 TW LION accelerator. The premise of this work is that multiple x-pinch plasmas, driven by pulsed power generators, might be capable of serving as a controlled, distributed XUV or soft x-ray "flashlamp" for resonantly photopumping a population inversion in a nearby secondary plasma (laser medium). The results from preliminary data analysis of a two month experimental run carried out from February to April 1989, are described in some detail in Appendix A. The following paragraphs summarize those results and discuss some of the implications. An experimental run carried out from November 1989 through February 1990 will be described in our next report.

Multiple x-pinch plasmas were produced using aluminum wires driven by the 0.5

TW LION pulsed power generator at Cornell. Bright XUV and soft x-ray spots were observed at each crossing point of the two wires. Tests were performed with from 1 to 7 such crossing points in the 3 cm interelectrode gap on LION. XUV spectra were obtained with a 1m grazing incidence grating spectrograph borrowed from the Laboratory of Laser Energetics, University of Rochester, thanks to Dr. Martin Richardson. (To protect the spectrograph, we also had to borrow a fast-closing valve from Dr. Keith Matzen's group at Sandia National Laboratories, Albuquerque.) Post run analysis of our data showed that we were probably overheating the plasma based on a goal of using a 76Å Al VIII line to resonantly photopump a Ne VII line.[1] In fact, one of the most prominent lines in our spectra was the Al XI line at 48Å (see Fig. 8 in Appendix A), which is suitable to photopump a Mg IX line.[1] Unfortunately, it is not clear right now how we might prepare a secondary, eight-times ionized magnesium plasma, although a capillary discharge similar to the one developed at NRL for Na may be possible. By contrast, a six times ionized Ne plasma might be generated by using a ~10J glass (or CO_2) laser to irradiate a very fine (cryogenic) Ne liquid jet. (The boiling point of Ne is about 26°C.) Regardless of which particular resonant photopumping laser scheme or schemes we pursue, it is clear that we must develop enough understanding, at least empirically, of the X-pinch source dynamics so that we can control the temperature and ionization state, and therefore the emission spectrum, of the bright spots.

One interesting feature of our experiments was that by twisting the wires at the crossing points, 3 or more separate $\lesssim 20\mu m$ bright spots were observed within about a $\frac{1}{2}$mm total source diameter, and XRD and PIN diode pulse widths were up to 30 ns long. This suggests that time coincidence of the pump radiation from the several crossing points will not be a problem if we twist the wires, so long as the spectra as a function of time from each source point are very similar. This is probably the most significant question yet to be addressed about the X-pinch source. It is high on the list of goals for our next experimental run, but its investigation requires us to be able to borrow the necessary

diagnostic equipment; we do not yet know if this is possible.

Please see Appendix A for a more complete presentation of the results of this experimental run, and of our preliminary analysis of those results.

III. Long Conduction Time Plasma Opening Switch Experiments

It is generally agreed now that the long conduction time ($\sim 1\mu s$) nnnopening switch is the element which will determine how soon inductive storage will be useful for generating <100ns, >1 TW pulses for nuclear weapons effects simulation and other purposes. The objective of this research is to study the fundamental processes underlying the operation of a planar plasma opening switch through the use of emission spectroscopy and advanced electro-optical diagnostics, in addition to the usual electrical diagnostics. The intention is to gain enough understanding of the physics of the operation of these switches that the required technical breakthrough does not have to be found by accident. This work is being carried out in collaboration with Dr. Gerald Cooperstein's branch at NRL.

Appendix B contains a copy of the poster presented on our parallel plate, long conduction time plasma opening switch experiment at the IEEE plasma science meeting (Buffalo, NY) May 22-24, 1989. That experiment involves the injection of a $\sim 10^{14}/cm^3$ carbon plasma (C^+, C^{++}, C^{+++}) into a 1cm gap between parallel plate electrodes. The plasma covers a 10 cm $\times$ 10 cm area.

The principal new results reported here concern the dynamics of the switch plasma as observed using sequences of 5 ns visible light frames obtained as a function of time (but on a pulse-to-pulse basis) during switch opening. These sequences, reproduced as well as we could manage, are included in Appendix B. The circled numbers on each frame are the time, referenced to the time of maximum dI/dt in the switch, as marked on the upstream and downstream current waveforms adjacent to the frames. The sample waveforms, at the top of each set show that the conduction time is typically 400–500ns, and the opening time is typically 150–200ns, although <150ns is obtained on some pulses.

We cannot be certain of the interpretation of these photographs because they are taken using visible light. However, the fact that the sequence obtained with all visible light (labelled "no filters") and sequence with an 500Å wide filter around 5000Å (labelled "taken with 500nmfilter"), used to eliminate the more intense neutral carbon lines, look very much the same suggests that we are looking at emission from plasma excited by current flowing through it. The apparent motion of the conduction channel during opening is striking. Notice also the bright plasma on both electrodes even after the switch appears to be open. Finally, we can also see the switch reclosing at late time.

Because of the many uncertainties associated with these measurements, we cannot use them to rule out models of switch opening except perhaps those based on a uniform current-carrying plasma channel prior to opening. However, even there, the fact that we do not have a symmetric configuration may mean we should not expect to see one dimensional opening switch dynamics either before or during opening.

IV. Theory of Plasma Opening Switches

By now, it is clear that the physics of plasma opening switches, and especially long conduction time opening switches, will have to be better understood before the operation of these important "circuit elements" will be predictable. In conjunction with the detailed experimental investigation, we are carrying out analytic and numerical studies of the penetration of the current into the plasma, the flow of electrons across the gap region, and the ultimate magnetic insulation of the anode-cathode gap. Our understanding of the operation of long conduction time plasma opening switches is as follows:

1. The current flows through the plasma in a time varying resistive sheath of thickness $\delta(t) \sim ct^{\frac{1}{2}}/(4\pi\sigma_*)^{\frac{1}{2}}$, t is the time from pulse initiation, σ_* is the anomolous conductivity $n_0 e^2/m_e\nu_*$ and the anomolous collision frequency is determined by the acoustic instability (Kulsrud et al., 1988). However, ν_* does not exceed a few times the ion plasma frequency ω_i because of nonlinear saturation effects

discussed by Sudan and Similon (1988).

2. The j $\times$ **B** force acts like a snowplow on the plasma moving at a speed $v_A = B_0/(4\pi n_0 m_i)^{\frac{1}{2}}$ where B_0 is the magnetic field at the plasma surface, $n_0 m_i$ is the plasma mass density before compression. The plasma density rises rapidly at the snowplow. In a time of order $\nu_*/2(\Omega_e\Omega_i)^{\frac{1}{2}}$ the fluid model breaks down and the ions are reflected at the electrostatic potential of the sheath; Ω_e and Ω_i are the electron and ion cyclotron frequencies. The reflected ions lead to two-stream instabilities and plasma heating.

3. The length of the plasma decreases because of snowplow action and the gap between the cathode and plasma widens as a result of erosion and j $\times$ **B** force. The electron flow between the cathode and the plasma is determined by the following steady state equations for a two-dimensional (x,y) model; no variations along $\mathbf{B} = B(x,y)\hat{z}$ are assumed i.e. $\partial/\partial z = 0$.

$$\nabla^2\varphi = 4\pi ne \tag{1}$$

$$\mathbf{j} = -ne\mathbf{v} = (c/4\pi)\nabla B \times \hat{z} \tag{2}$$

$$\nabla\frac{u^2}{2} - \mathbf{u}\times\nabla\times\mathbf{u} = \frac{e}{m_e}\gamma\nabla\varphi - \frac{e}{m_e c}\,\mathbf{u}\times\mathbf{B} \tag{3}$$

$$\mathbf{u} = \gamma\mathbf{v}\ ; \qquad \gamma = \sqrt{1+u^2}/c^2. \tag{4}$$

From Eqn.(2) one obtains

$$u^2/c^2 = |\nabla B/4\pi ne|^2\{1 - |\nabla B/4\pi ne|^2\}^{-1}. \tag{5}$$

From the mass and momentum conservation it is possible to arrive at the following constant of motion

$$n/(\Omega_e - \omega) = constant \tag{6}$$

where $\omega = \hat{z}\cdot\nabla\times\mathbf{u}$.

4. The current to the plasma interrupts when no solution to Eqns. (1) to (5) can be found for the plasma geometry, length L and gap d, with the correct boundary conditions at the cathode and $\varphi = \varphi_0$ the open circuit voltage at the plasma surface, for the appropriate current.

5. We are struggling to set up a correct procedure to solve Eqns. (1) to (5).

V. Advanced Electro-Optical Diagnostics for Opening Switch Plasmas

An unsuccessful attempt was made to measure the density gradient in the plasma from an NRL flashboard using the deflection of a HeNe laser directed across the plasma [2], evidently because the flashboard plasma density is below $10^{14}/\text{cm.}^3$ However, an experimental system was set up involving a 1m spectrograph and the NRL flashboard to fully characterize the plasma from that source spectroscopically. The actual experiments were carried out during calendar year 1990 and results will be described in our next report.

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APPENDIX A

X-RAY SOURCE CHARACTERIZATION OF ALUMINUM X-PINCH PLASMAS DRIVEN BY THE 0.5 TW LION ACCELERATOR

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ABSTRACT

Recent experiments at Cornell have been performed to investigate X-pinch plasmas as intense x-ray sources which might be used to pump resonant photo-excitation lasers. Crossed Al wires have been driven by up to 600kA current for 40ns. High density bright spots are observed at the crossing point(s). Various diagnostics were used to characterize the X-pinch plasmas as a function of initial mass loading for several specific wire configurations. The optimum mass loading for different ionization stages of Al, and the total x-ray energy yields, which are on the order of hundreds of Joules, were examined. Estimates of plasma density, $\sim 10^{20}\mathrm{cm}^{-3}$, and temperature, about 400eV, were obtained.

INTRODUCTION

The plasma generated in an X-pinch, in which two or more crossed wires are exploded by a large current from a pulsed power generator, emits an intense burst of XUV and/or X-ray radiation. As the source is spatially localized, and the photon energy of the radiation can be varied by changing the wire material, it is potentially suitable for development as a photo-pump for soft X-ray lasers.[1,2] Other possible applications include X-ray microlithography,[3,4] microscopy,[5,6] and spectroscopy.[7]

This paper reports preliminary results of recent X-pinch experiments at Cornell using aluminum wires. The principal goals were to produce spatially confined bright radiation spots in single or multiple cross X-pinches, to characterize their emissions, and to optimize the radiation yield in certain spectral lines by varying the mass loading and the specific wire configurations. Wire loads mounted on the 0.5TW LION accelerator included 2 or more wires touching or twisted at a single crossing point, 2 wires twisted at up to 7 points in the 3 cm long LION load region, and multiple parallel wires for comparison. Radiation emission intensities, plasma parameters, the size of the bright spots, and degree of ionization were determined with diagnostics which provide temporal, spatial, and spectral information. Total Al K-shell radiation energy yields as high as several hundred Joules were measured, and the energy in the resonance lines of Al XI and Al X ions were on the order of 0.1 Joules. Based upon the results of these and future experiments, we will investigate potential resonant photopumped laser schemes such as those involving *Be*-like ions,[8] using the multiple cross X-pinch radiation emission as a controlled, distributed pump source.

EXPERIMENT AND RESULTS

Figure 1 shows the apparatus of the X-pinch experiment. The 3 cm diameter anode is located on the z-axis and is surrounded by 8 return current rods on a 6 cm diameter circle. Two to four Al wires were stretched across the 3 cm load gap, as shown in Fig. 1. The line density of the wire load was varied from 10 to 1000μg/cm by changing wire diameters and varying the number of the wires.

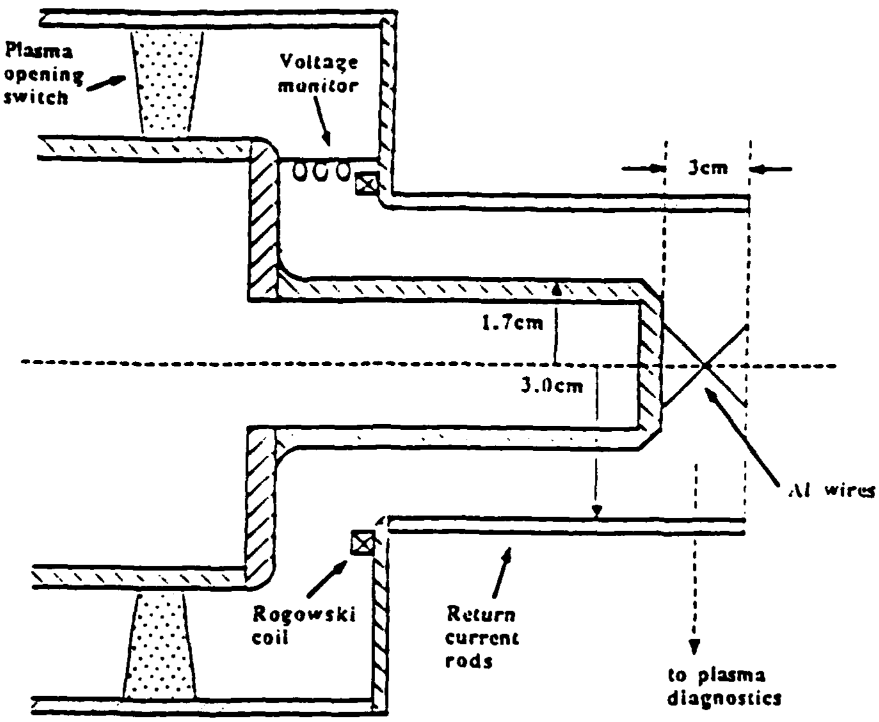

Fig. 1. Schematic diagram of the experimental apparatus.

All of the diagnostics are mounted around the vacuum chamber to view radially. The Al K-shell radiation intensity was measured with a filtered PIN diode (Quantrad Corporation 100-PIN-250). Soft X-ray radiation was detected by using Al cathode x-ray diodes (XRDs) filtered with 4μm and 6μm thickness mylar foils coated with 1000Å Al. An XUV and soft x-ray pinhole camera was used to 'photograph' the radiation emission region, and to determine the size of the source. Two pieces of Kodak TMX400 or 101 x-ray film were placed, one behind the other, in the camera so that the first film imaged Al L-shell and K-shell radiation, while the second film, filtered by the first film in addition to the common 4μm mylar foil coated with 5000Å Al, imaged only K-shell radiation emission. A 5ns visible light single frame camera was used to view the plasma formation and development by varying the frame timing with respect to the time of peak current. Aluminum K-shell and L-shell spectra were obtained using a crystal spectrograph and a 1m grazing incident spectrograph, respectively.

In the experiments, the nominally 0.5TW LION accelerator was charged to about 80% of its maximum voltage, namely 80 kV. Power pulses of 60ns (fwhm) duration and peak currents of 500-600 kA were delivered to the X-

pinch load. Shown in Figs. 2-4 are data from a typical single cross experiment. The configuration of the particular pulse shown was two Al wires, each of them 50μm in diameter and about 50μg/cm in line density, touching at one point. Figure 2 shows the load current and voltage waveforms. The peak current was 500-550kA and it lasted about 40ns at that level. Peak power delivered to the load was 0.25 TW. The signals of the filtered XRDs and the PIN diode are shown in Fig. 3, in which it is evident that the pulse width of the radiation emission is about 10ns. Figure 4 shows the 5ns visible framing camera image at pinch time. A bright spot is evident at the cross point. A corresponding bright spot is also visible in Al K-shell emission in the pinhole photograph. The sizes of the Al K-shell bright spots are estimated to be about 20μm or less from the pinhole camera images.

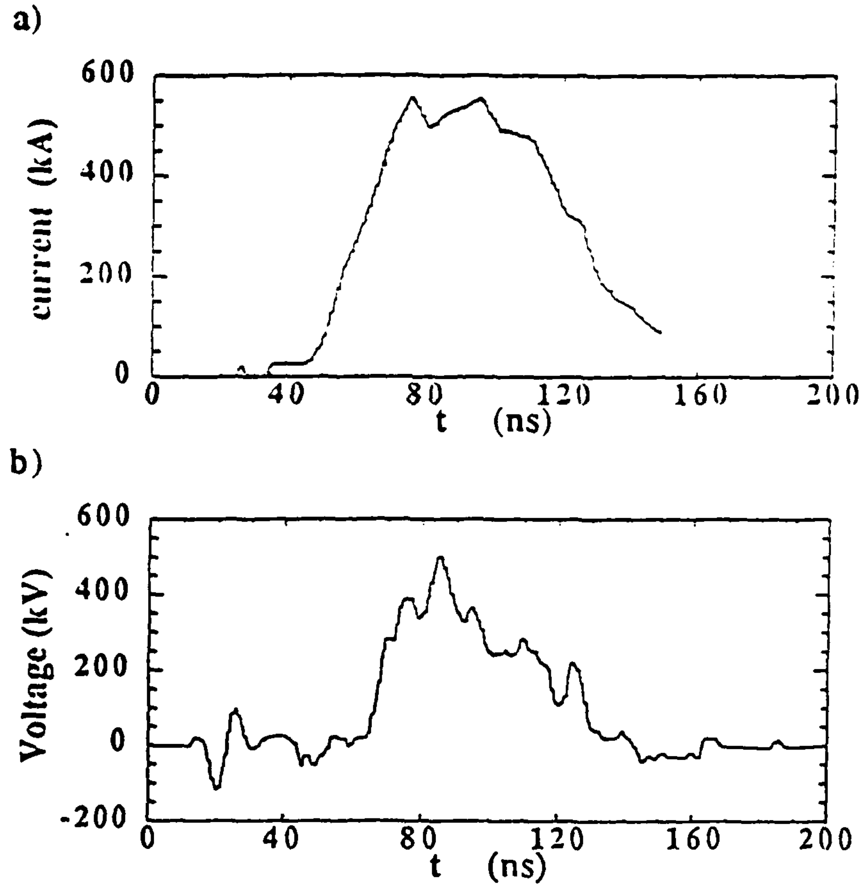

Fig. 2. Current (a) and voltage (b) waveforms for a single cross X-pinch pulse (No. 677).

In the energy region from 300 to 1500eV, there is no strong line radiation emission from the Al ions. The plasma temperature can be estimated from filtered XRDs since the spectrum in this region is dominated by continuum radiation. Figure 5 shows the electron temperature obtained by this method as a function of the initial mass loading in the single cross configuration.

The relative Al K-shell radiation intensity was monitored by using the PIN diode. To obtain an estimate of the absolute, time integrated Al K-shell radiation yield, the PIN diode was calibrated by comparing the integral of its

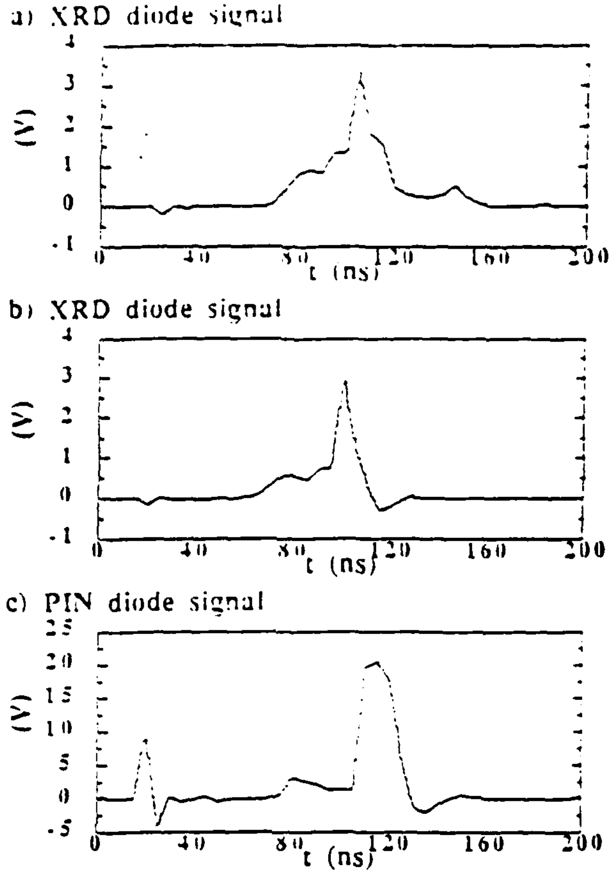

Fig. 3. X-ray diagnostic waveforms showing (a) the XRD signal filtered with $4\mu m$ mylar foil, (b) the XRD signal filtered with $6\mu m$ mylar foil, and (c) the PIN diode signal for the same pulse as shown in Fig. 2.

Fig. 4. The visible light image at pinch time using the 5ns visible framing camera for the pulse shown in Fig. 2.

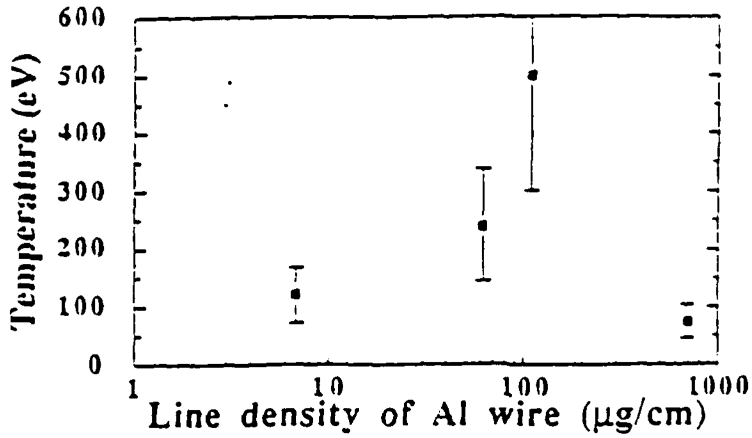

Fig. 5. Plasma temperature versus mass loading.

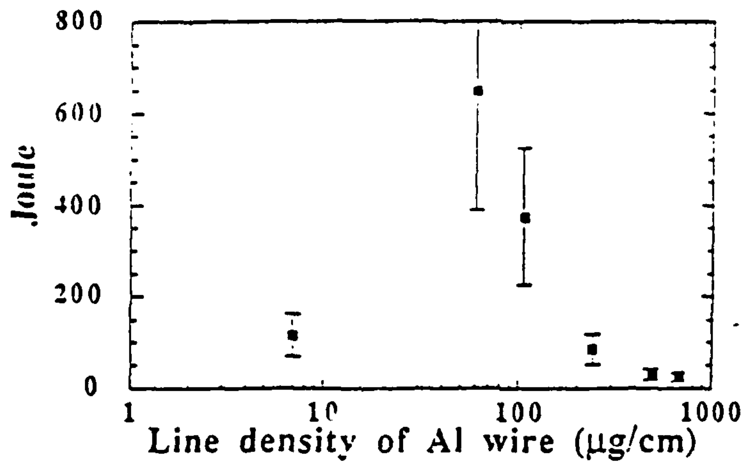

Fig. 6. Measured Al K-shell radiation yield as function of the mass loading.

signal with the radiation energy on a Kodak Type 101-07 film exposed behind a $10\mu m$ Al foil in a $475\mu g/cm$ mass loading single cross shot. However, because it was found later that the x-ray film was saturated, the total K-shell radiation yield in Joules as a function of the mass loading in the single cross configuration shown in Fig. 6 is a lower limit of the yield. Peak radiation yield observed on the PIN diode was obtained at 60-$100\mu g/cm$ initial mass loading, where the lower limit yields ranged upward from 200 Joules. Figures 7 and 8 are the Al K-shell and L-shell time integrated spectra, obtained by using the crystal and the 1m grazing incident spectrographs, respectively. Emission lines of H-like Al ions were not observed, which suggests the electron temperature of the bright spots was 300eV or less,[9] as compared with about 500eV obtained from the filtered XRD ratios (Fig. 5).

The relative line intensity ratio of resonance and intercombination lines in the spectrum of He-like Al ions is strongly dependent on electron density.[10] The estimated electron density from this ratio is estimated to be $10^{20}cm^{-3}$. In the L-shell spectrum, most emission lines are from Al IX ions. Thus, the electron temperature in the region emitting these lines is estimated to be $120 \pm 50eV$.

Detailed analysis of the data is in progress and will soon be published elsewhere.

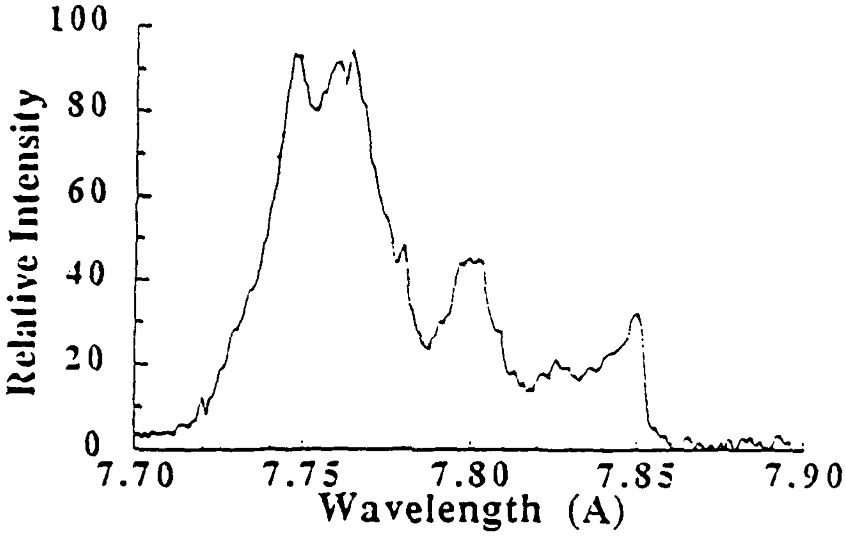

Fig. 7. K-shell spectrum from a single cross X-pinch pulse (No. 705).

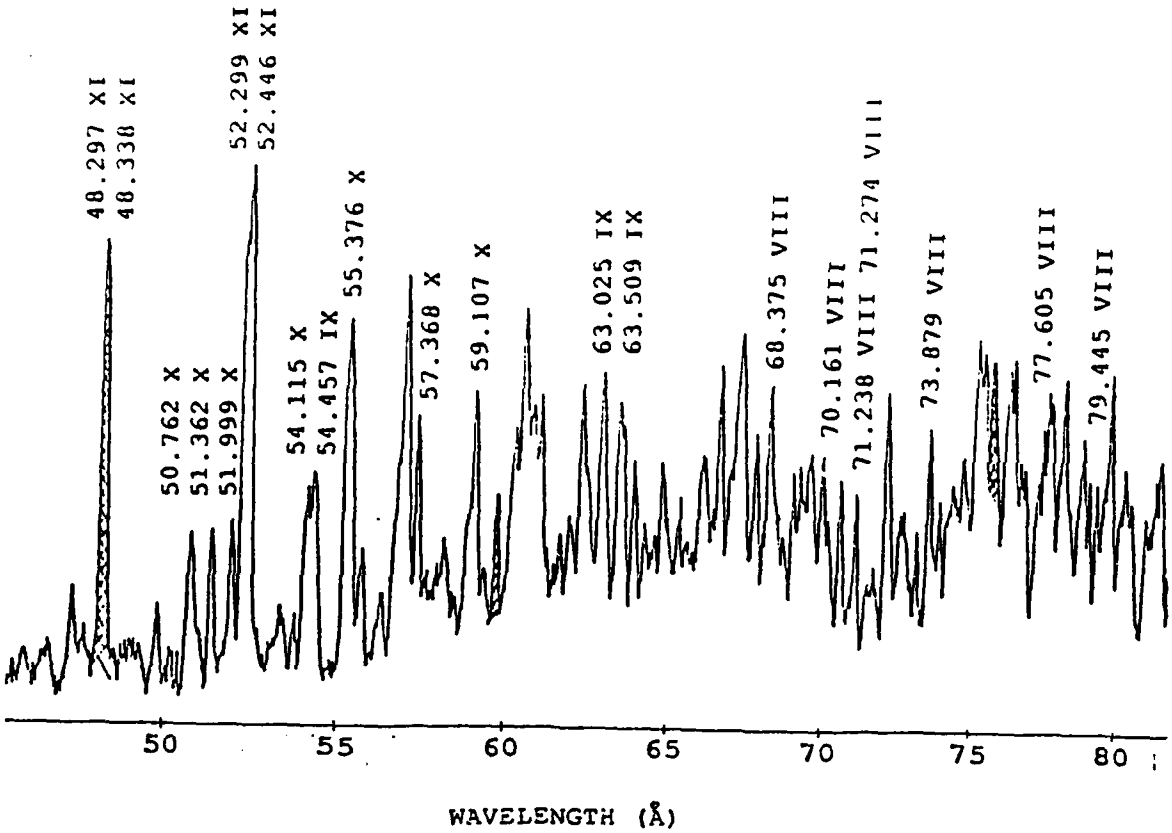

Fig. 8. L-shell spectrum from a four parallel wire pulse (No. 714).

In addition to the simple, single cross, several other configurations were tested, specifically multiple-cross (2-7 crosses) X-pinches, and four parallel (on 0.5 and 1.0 cm diameter circles) wire implosions. Figure 9 shows the 5ns visible framing pictures of two of these plasmas at pinch time. In the multiple cross X-

pinch confi[illegible] spot from each cross point was observed on the Al K-[illegible] the peak K-shell radiation is shifted to lower mass lo[illegible] In four parallel wire implosions, K-shell radiation was [illegible] PIN diode. the pulse width of the radiation on the XRDs [illegible] ns. and the intensity was weak compared with an X-pinch.

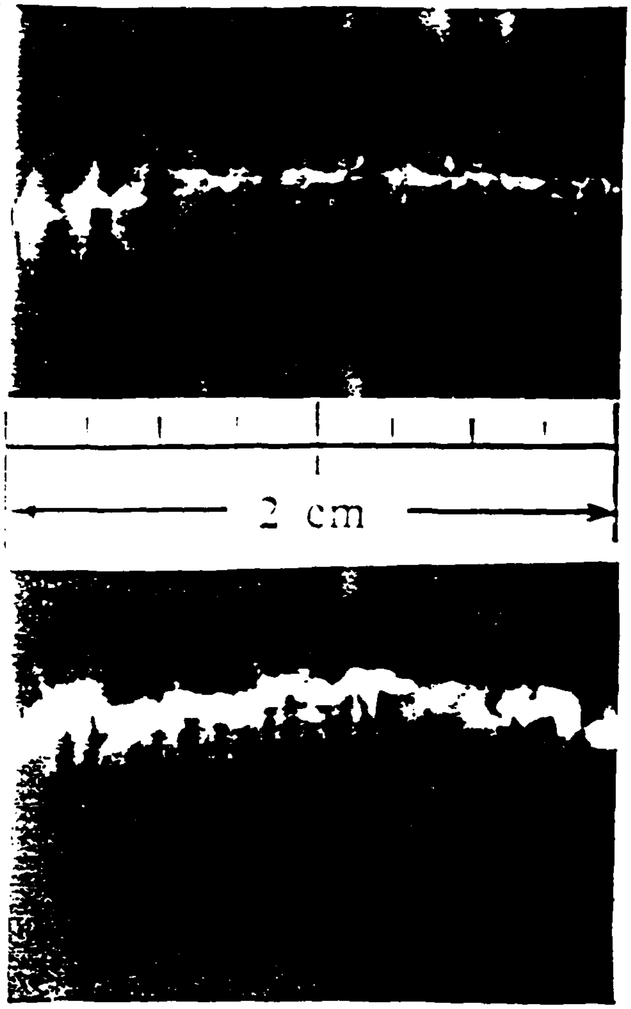

Fig. 9. The visible light images of the plasma at pinch time using the 5ns visible framing camera for a multiple cross X-pinch pulse (top), and a four parallel wire pulse (bottom).

DISCUSSION

We believe that the bulk of the XUV and soft x-ray emission we observed comes from the region where the wires touch each other, based upon the time integrated pinhole photography. The plasma conditions of the bright spots and/or immediately surrounding area were estimated from XUV and soft x-ray spectroscopic diagnostics to be 100-500 eV depending upon loading. As already noted, Helium-like Al line emission yielded an estimated density in the $\leq 20\mu m$ bright spots of about $10^{22}cm^{-3}$, assuming all electrons are in thermodynamic equilibrium. This suggests that only a few thousandths of the initial wire mass

per unit length is participating in the brightest part of the X-pinch.

A controlled, distributed radiation source is generated by using multiple cross X-pinches, which may be a suitable photon source for resonance photo-pumping soft X-ray lasers. Questions as to the radiation power of possible pump lines, and the coincidence in time of radiation from all of the bright spots will be addressed in future experiments.

ACKNOWLEDGMENTS

The authors wish to thank Dr. John Apruzese and Dr. Jack Davis for several valuable discussions, and Dr. M.K. Matzen and his group at Sandia National Lab., Albuquerque, for lending us the fast closing valve used in these experiments. We are also grateful to G. Bordonaro for technical assistance, and to L.K. Adler and W.A. Noonan for their assistance in some of these experiments. This work is supported by the Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375-5000 under ONR Contract N00014-89-J-2009; funding for this task was provided by SDIO.

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APPENDIX B

presented IEEE conference May 1989 Buffalo, NY

Time Resolved Plasma Characterization in a Long Conduction Time Planar Plasma Opening Switch*

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The success of relatively small and inexpensive pulsed power systems based on inductive energy storage depends on the development of efficient fast opening switches. The long conduction time plasma opening switch (POS) is a good candidate for the last stage opening switch in such a system. A basic understanding of the mechanisms involved in opening are needed to optimize the behavior of these switches. At present they are characterized by longer switching times and more losses than the short conduction time switches.

A system with circuit characteristics much like Naval Research Laboratory's POP[1] experiment has been constructed. The system has an inductance of 300 nH (no plasma in switch, short circuit load) with 10 nH of this downstream of the POS. The system is pulsed by a 1.9 μf Scyllac capacitor charged to 50 kV. The plasma for the 10 cm $\times$ 10 cm planar switch is provided by a Mendel-type carbon plasma gun[2] which is pulsed by a 2.0 μf capacitor charged to 20 kV. This supplies a plasma with roughly 3×10^{14} cm^{-3} ion density, predominantly C^{++}, with some C^{+++}, with an electron temperature of 10–15 eV.

A recently completed run with this switch plasma gave conduction times up to 400 ns, with an opening time of 130 ns, delivering 70 kA (out of 106 kA available) into a short circuit load. An electron beam diode load gave 220 ns conduction time and 190 ns opening time with 70 kA (out of 100 kA available) delivered to the diode with some voltage multiplication.

We will also discuss additional experiments in which the plasma dynamics and properties will be monitored in detail before and during opening. Space and time resolved density, temperature and motion information about the plasma and neutrals is given by emission spectroscopy and streak photography and correlated to the current and voltage traces. Specifically, we will look for the effects of neutrals evolving off of surfaces, stagnation of the switch plasma, and $\vec{J} \times \vec{B}$ motion of the plasma downstream of the switch. Diagnostics include current and voltage monitors, a multi-aperture biased Faraday cup, emission spectroscopy and streak photography. Pairs of $\dot{B}$ dot loops are positioned in the stripline just upstream and downstream of the POS. Also, two single $\dot{B}$ loops were placed further downstream to look for bulk plasma motion. An inductive monitor gives the voltage at the upstream side of the POS and the Faraday cup monitors the gun plasma consistency from shot to shot.

*Work supported by the Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375-5000 under ONR Contract N00014-85-K-0212.

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[2]C.W. Mendel, Rev. Sci. Instrum. 51, 1641 (1980).

INTRODUCTION

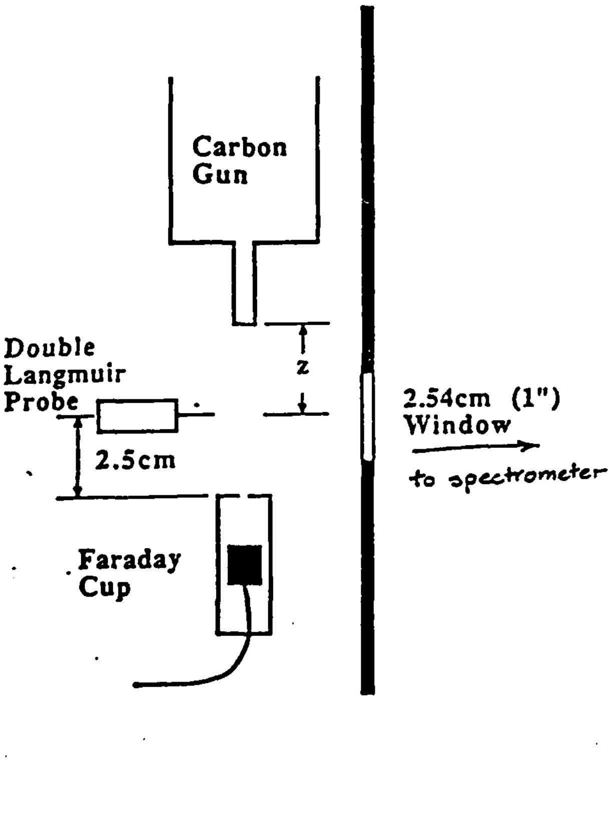
Very fast opening switches are important for pulsed power. They can provide pulse compression and voltage gain. Inductive storage can provide cheaper and more compact pulsed power machines but depends on fast, efficient opening switches. The plasma opening switch, POS, which can open as fast as 10 ns, is a good candidate for a fast reliable opening switch. The POS has been used successfully to increase the power output of many of the present large pulsed power machines. But many issues remain unresolved about how these switches work. Basic questions about scaling of losses, causes of reclosure and changing performance with varying load impedence and impedence profiles are only partially answered. Much modelling and computational work has gone into trying to understand the operation of these switches but few measurements in the switch plasma have been made to support the theoretical work.

PURPOSE

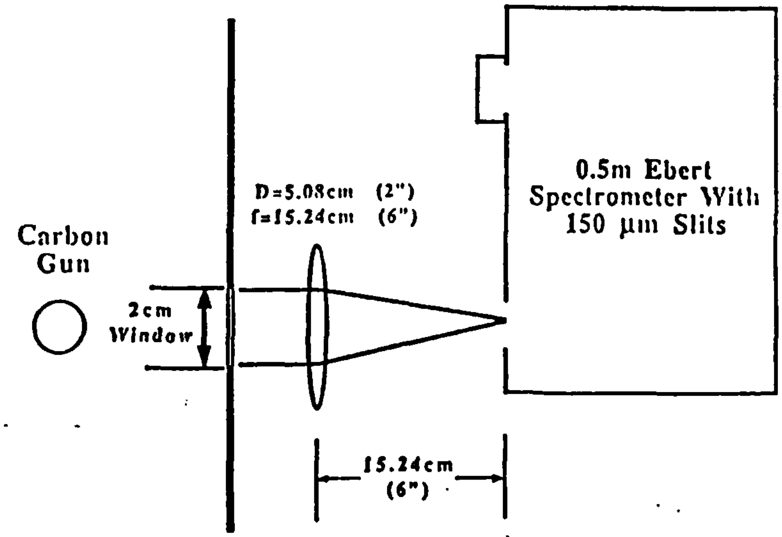
The purpose of this experiment is to make non-intrusive measurements of the plasma in a planar long conduction time POS by studying the light emission. Emission spectroscopy will be coupled to full set of voltage and current diagnostics to track the plasma conditions at various stages in the switching process. As a first step, the plasma from a Mendel-type carbon plasma gun was studied using emission spectroscopy, a double Langmuir probe, and a Faraday cup. Density and temperature information about the freestreaming carbon plasma was obtained. Next a long conduction time POS was constructed with parameters similar to Naval Research Laboratory's POP[2] experiment. The most recent work has been some framing photograpy done as a survey before commencing the emission spectroscopy.

CHARACTERIZATION OF CARBON PLASMA

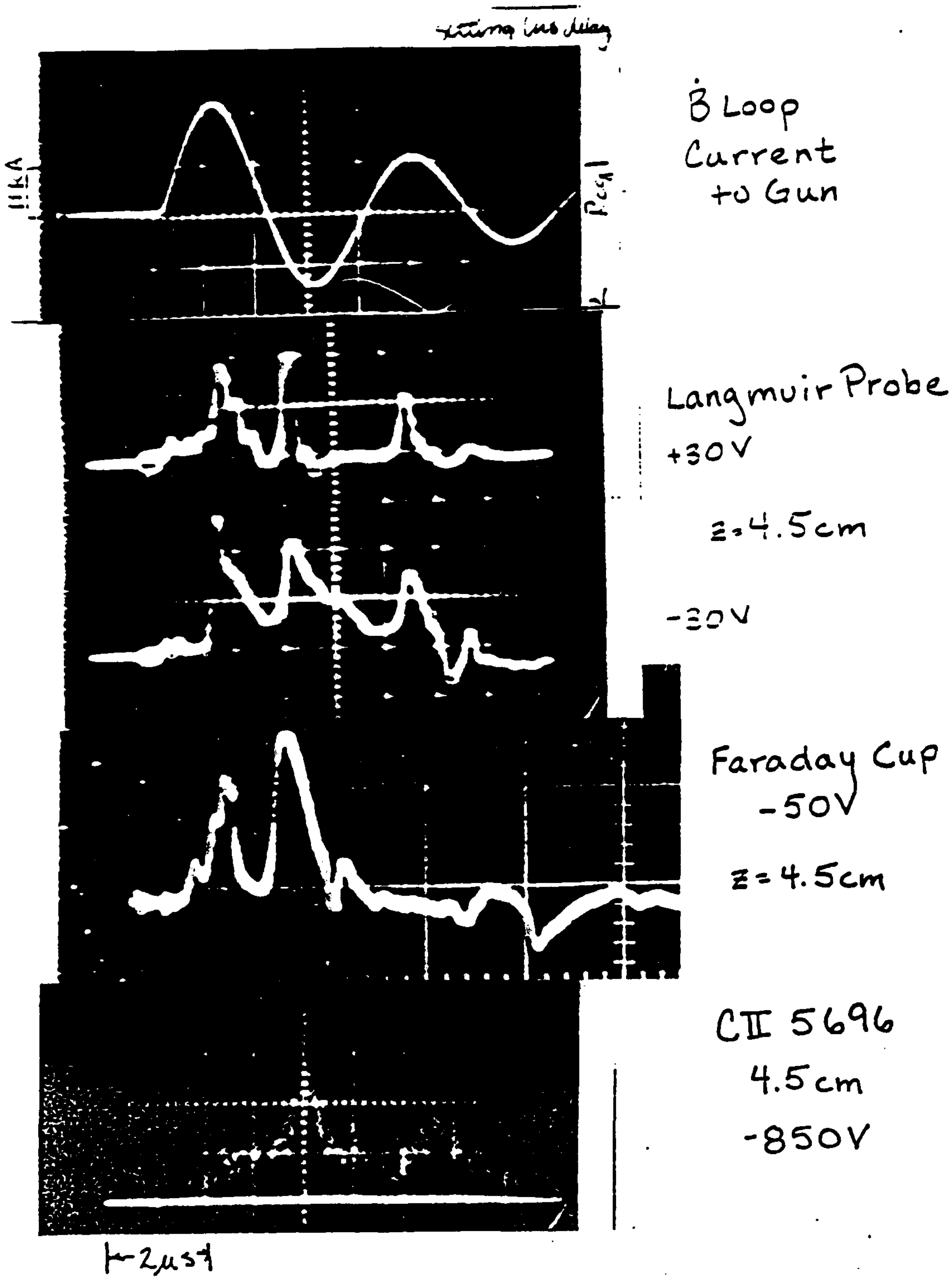
The Mendel-type Carbon gun was fired with a 20 kV pulse from a 1.98 μf capacitor. System inductance was measured to be 226 nH. Peak current was 26 kA. Diagnostics used to characterize the plasma were emission spectroscopy, a double Langmuir probe and Faraday cups. Emission spectroscopy gave time of flight velocity information and density measurements using a computer code including effects important to low density plasmas ($<10^{16} cm^{-3}$) assuming temperatures >5 eV. The computer code was provided and run by Dr. Niansheng Qi. The Langmuir probe gave temperature and density information. The Faraday cups gave time of flight velocity information, a rough monitor of plasma consistency as well as approximate density information.



OPTICAL SETUP FOR AVERAGING OVER LARGE PLASMA VOLUMES



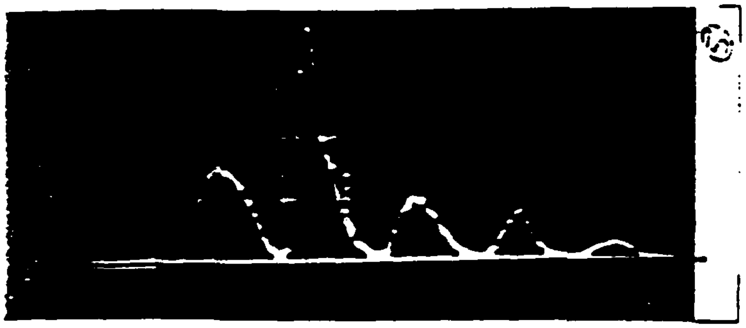
TIME CORRELATION OF DIAGNOSTICS



The first two peaks in each trace correspond. The Faraday cup does not detect the ions after the second peak. In the other traces the third and fourth peaks correspond shifted from the gun current peaks due to the distance from the gun and the difference in velocities. C II is C+, C II is C++, C IV is C+++ and C I is neutral carbon.

CARBON LINES

C IV 5812 Å



C III 5696 Å

Faraday Cup
-50V

C II 4267 Å

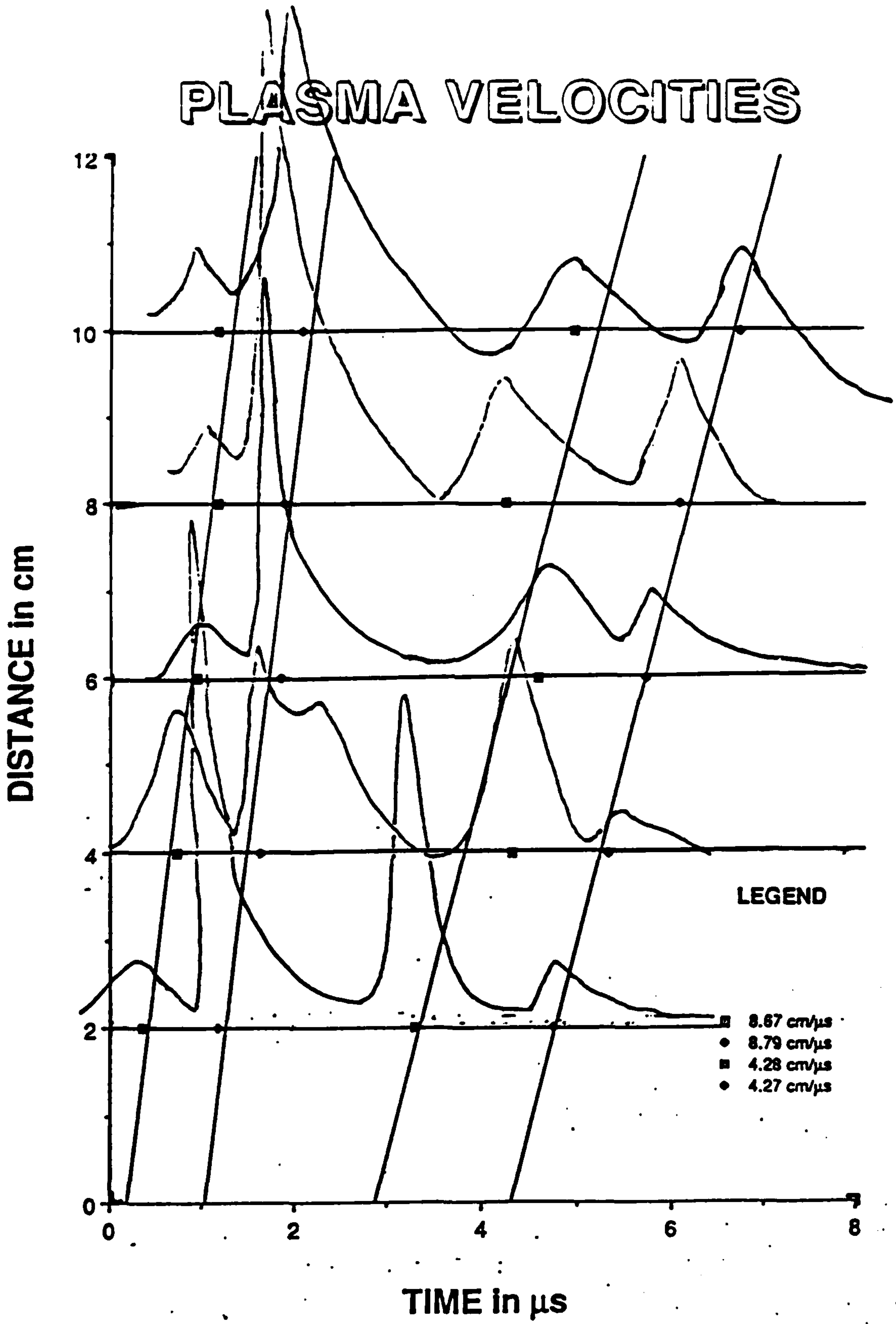
1 div = 1 μs z = 4.5cm

C I 6006 Å

1 div = 2 μs z = 4.5cm

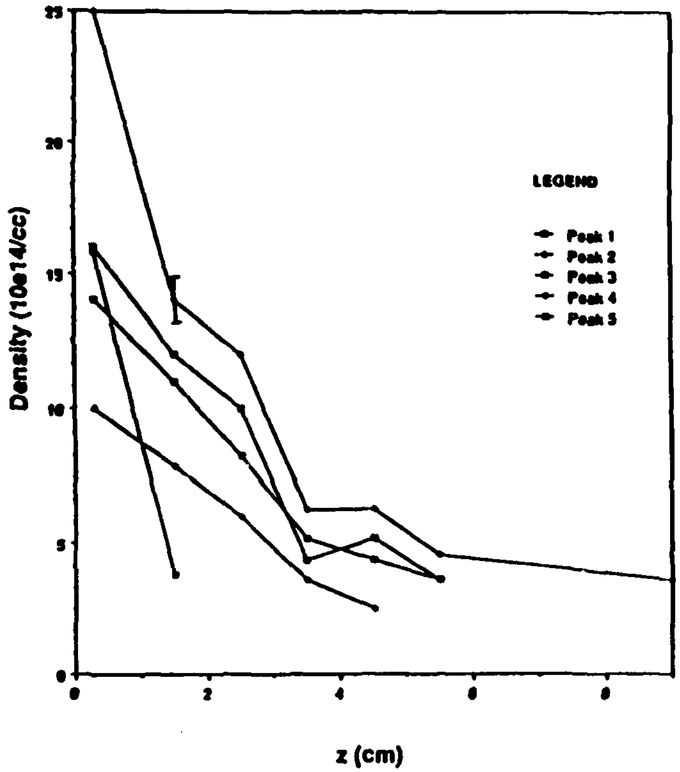
Photomultiplier tube traces show good correspondence of all the peaks of emission of the various ionization states of carbon.

PLASMA VELOCITIES



Photomultiplier tube traces for C II emission at 4267A. Positions of the peaks are marked along the baseline which is aligned with the distance from gun z.

DENSITY FROM ABSOLUTE INTENSITY OF CIII 5696Å



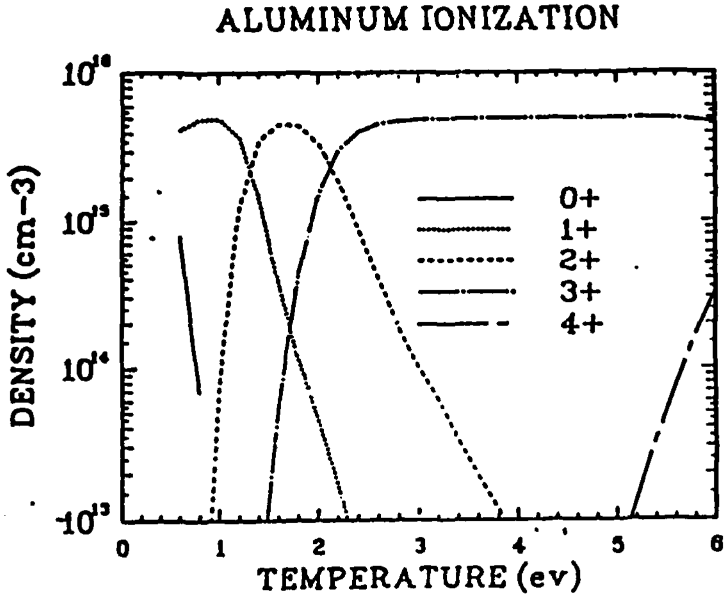
DENSITY AND TEMPERATURE

Burst	Distance (cm)	Densities/cm³ Faraday cup	Abs. Intens.	Langmuir Probe
1	0.3		1.6×10^{15}	
	2.0	9×10^{13}	1.1×10^{15}	
	4.0	$8 \pm 2 \times 10^{13}$	5×10^{14}	5×10^{14}
	6.0	9×10^{13}	4×10^{14}	
	8.0			
	10.0	9.6×10^{13}		
2	0.3		2.5×10^{15}	
	2.0	9×10^{13}	1.3×10^{15}	
	4.0	$1.1 \pm .1 \times 10^{14}$	6.3×10^{14}	$\geq 7 \times 10^{14}$ *
	6.0	6×10^{13}	4.6×10^{14}	
	8.0	1×10^{14}	3.6×10^{14}	$\geq 7 \times 10^{14}$ *
	10.0	1×10^{14}		
3	0.3		1.4×10^{15}	
	2.0	3×10^{13}	9.6×10^{14}	
	4.0	$4 \pm 2 \times 10^{13}$	4.8×10^{14}	5×10^{14}
	6.0	4×10^{13}	3.6×10^{14}	
4	0.3		1×10^{15}	
	2.0	1.4×10^{13}	7×10^{14}	
	4.0		3×10^{14}	4×10^{14}
5	0.3		1.6×10^{15}	
	1.5		3.8×10^{14}	
	2.0	1.4×10^{13}		

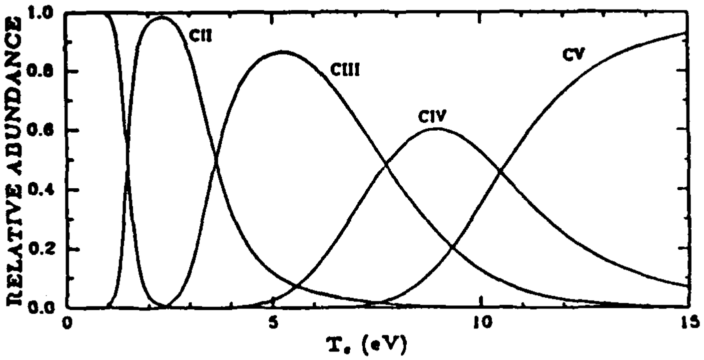
Burst	Distance (cm)	Temp (eV)
1	4.5	9 ± 1
2	4.5	$\geq 22 \pm 7$ *
	9.0	$\geq 18 \pm 2$ *
3	4.5	$> 13.4 \pm 1$
4	4.5	14 ± 1

* did not reach saturation

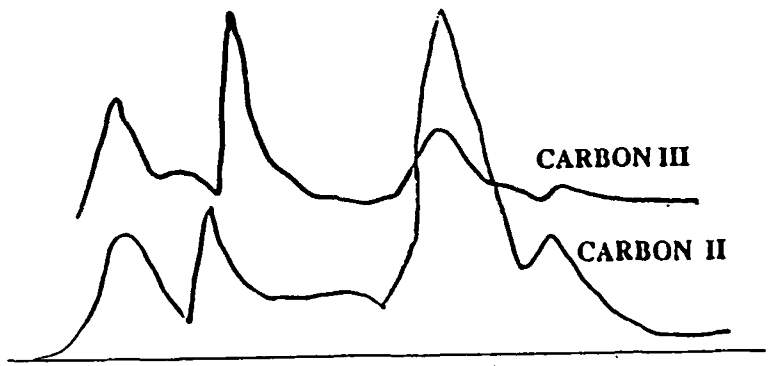
Densities from Langmuir probe and absolute intensity measurements agree well. The Faraday cup measurement is consistently low but is not always detecting all the ions present especially lower energy ions in the later bursts of plasma. The variation from peak to peak was consistent with other measurements. The errors quoted are those calculated from scatter in the data from shot to shot.



CARBON



Variation of the relative abundance of the ionization states of Aluminum and carbon with temperature.



Comparison of the C II and C III line emission shows the maximum of C II density to be before the C III maximum of the second peak. A small broad peak in the C II emission after the C III peak is also seen.

OBSERVATIONS

The presence of C III, C IV, and Al III and the absence of C I and Al II point to temperatures which agree well with Langmuir probe measurements. There is a difference in when the C II, and the C III and IV emission is maximized. This does not change with distance from the gun, z, over the range of 2 - 9 cm. The peak of the C II second burst is shifted to earlier time but moving at the same velocity as the peak of the C III second burst.

IMPLICATIONS

Careful examination of the peak of the C II second burst reveals that there is a sharp large peak coming before the normal peak of C III emission for this burst of plasma and a smaller broader one afterwards with a dip corresponding to the time of the peak of C II emission. This suggests that C II can only survive in the cooler outer regions of the second plasma burst which has a higher density and temperature gradient at the front and a gentler gradient at the back.

SUMMARY

The velocity, temperature and density of the plasma produced by a Mendel-type carbon plasma gun was measured. Different diagnostics agreed fairly well. The temperature, although not known precisely, agrees between the appearance of certain emission lines and a Langmuir probe determination. Since the second burst of plasma travels slightly faster than the first, at large distances they will merge. The emission from the second burst of plasma shows that this relatively hot dense plasma is most sensitive to shot to shot changes.

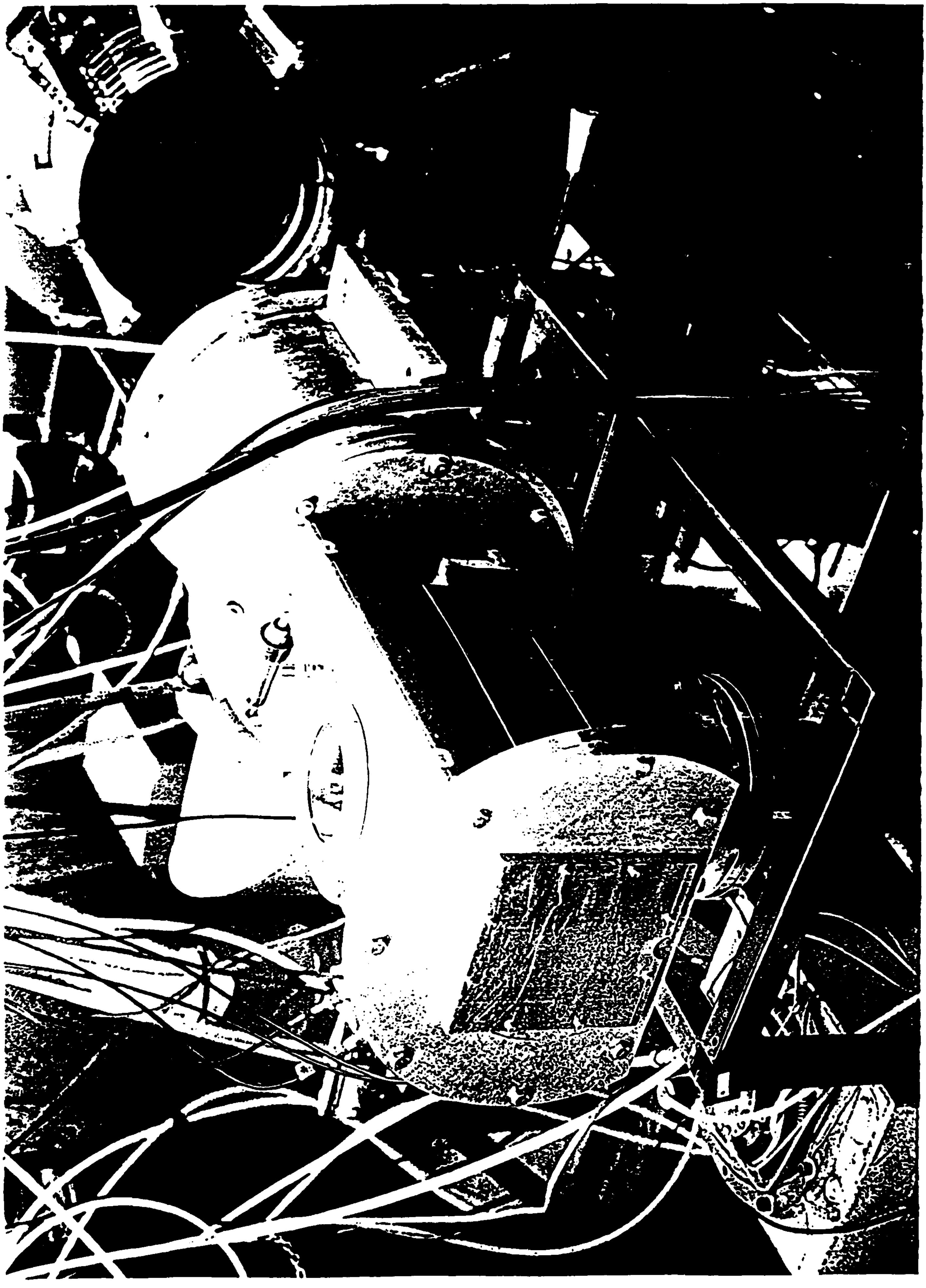
PLANAR PLASMA OPENING SWITCH

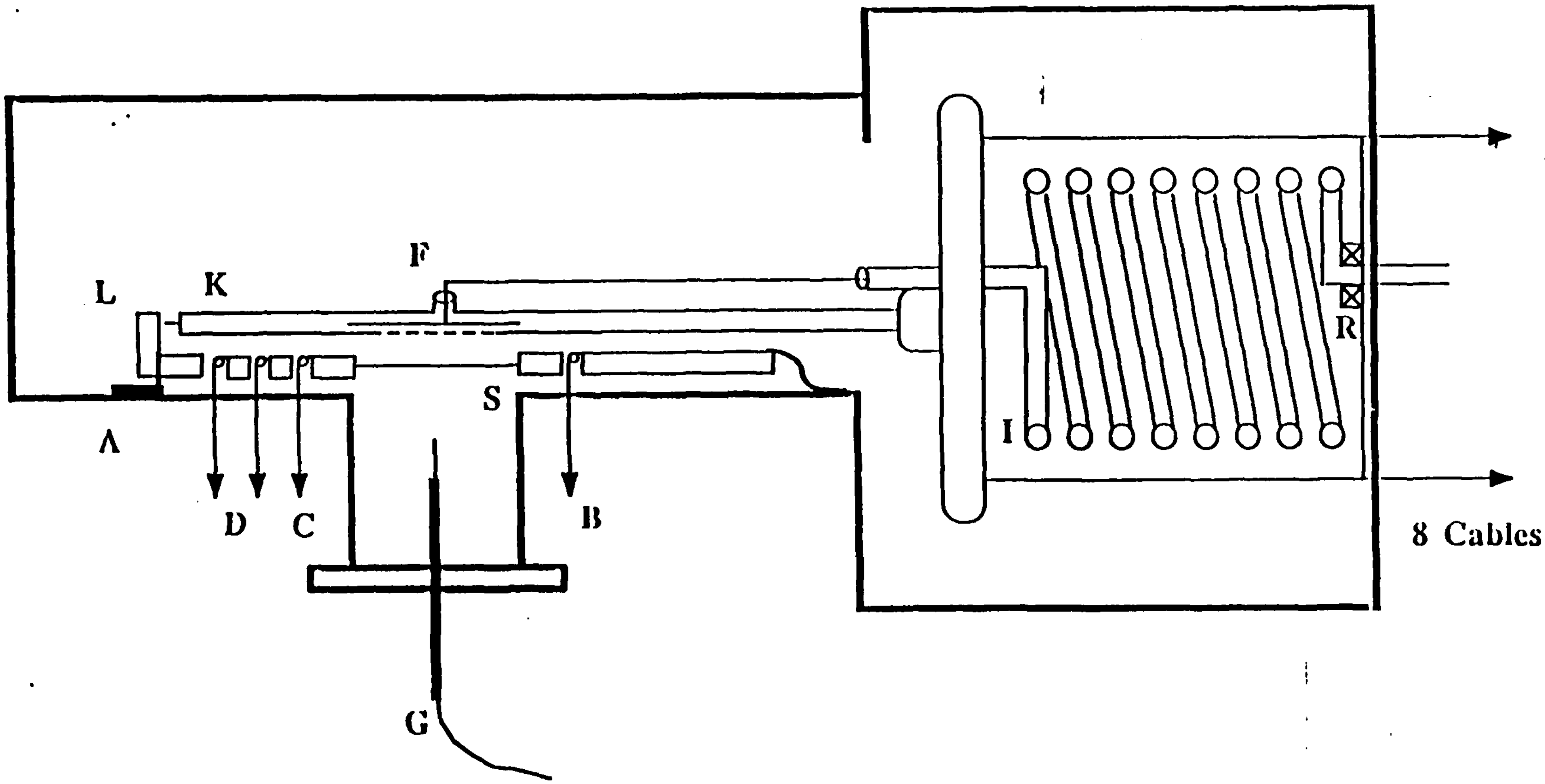
Preliminary work on the operation of the POS into short circuit and electron beam diode loads has been accomplished. Best opening seemed to depend most upon the output of the Carbon plasma gun as monitored by a multi-aperature biased Faraday cup. The Faraday cup indicates an average ion density of 6×10^{12} cm^{-3} at a time slightly before opening. The characterization studies done earlier give an expected ion density of ~ 3×10^{14} cm^{-3}. This suggests that the Faraday cup is not detecting some of the density in the switch since the gradient across the plasma is not that large. Spectroscopic studies should clarify this result since it can see cooler and less directed plasmas that the Faraday cup has trouble detecting.

The opening variation with delay between the gun firing and the switching of the main pulse was investigated. The best overall shot conducted for 400 ns opening in 130 ns to a current of 70 kA into a short circuit. Up to 118 kA was conducted, minimum opening time was 94 ns and the longest conduction time was 400 ns all into a short circuit. Very preliminary studies with an electron beam diode load were conducted.

CIRCUIT PARAMETERS

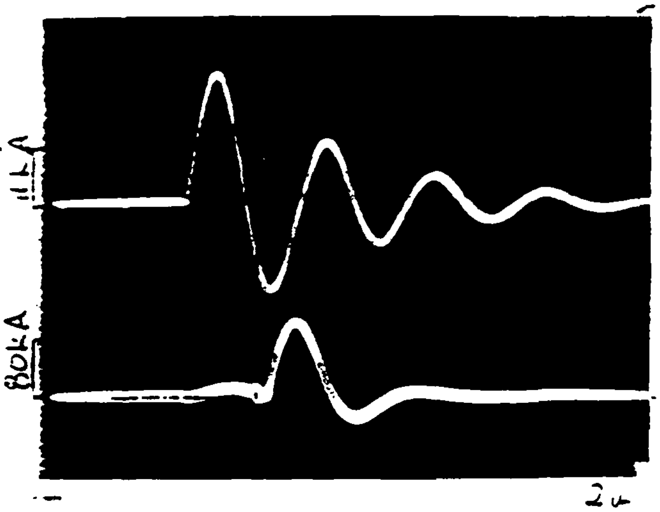
CARBON GUN	1.98 µf Capacitor
	226 nH system inductance
	20 kV charging voltage
MAIN VOLTAGE PULSE	
	1.93 µf Capacitor
	302 nH system inductance (no plasma, short circuit)
	50 kV charging voltage





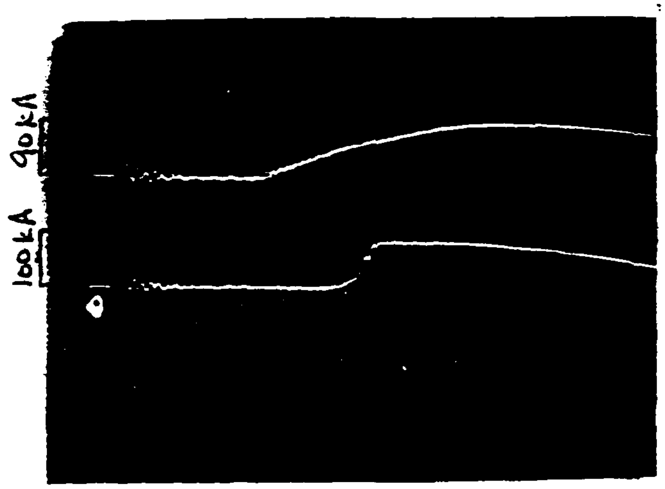
300 nH system Inductance (no plasma, short circuit):
K - Cathode pulsed at -30 to -60 kV from 1.93 μf Scyllac Capacitor
A - Anode–grounded 9mm A-K gap
G - Mendel-type carbon gun pulsed with 20kV from 1.98 μf Scyllac Capacitor - 16cm from Cathode
S - 10cm x 10cm aperature for carbon plasma - current return via rods
L - Short circuit or blunt carbon cathode electron diode load (diode load shown)

Diagnostics:
B - upstream current monitor - pair of $\dot{B}$ loops added
C - downstream current monitor - pair of $\dot{B}$ loops added
D - additional single $\dot{B}$ loops farther downstream
F - Multi-aperature biased Faraday cup
I - Inductive divider for switch voltage measurement - 1/2" Cu tubing, 17 turns, 27.3 μH
with 4 mini rigid coax inside
R - Rogowski for voltage monitoring

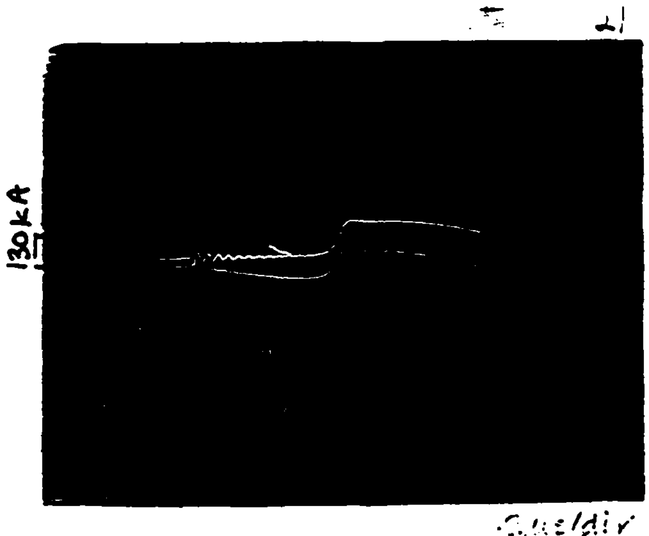


Gun current monitor
Main pulse current monitor
2 µs/div

Switch voltage monitor
Faraday cup -50V bias
.2 µs/div



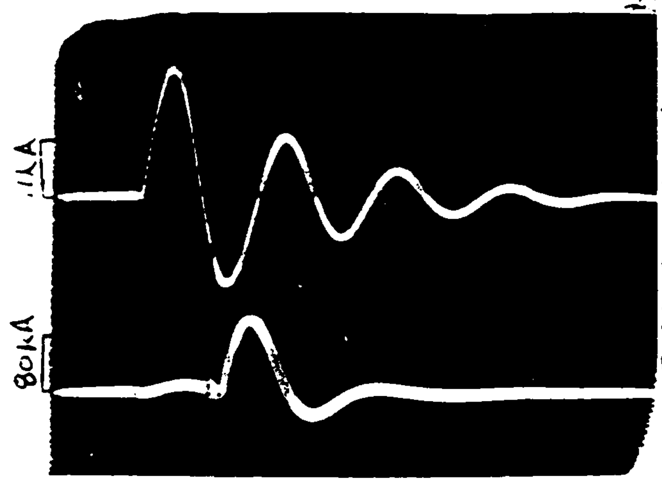
upstream current monitor
downstream current monitor
.2 µs/div



further downstream
current monitor
.2 µs/div

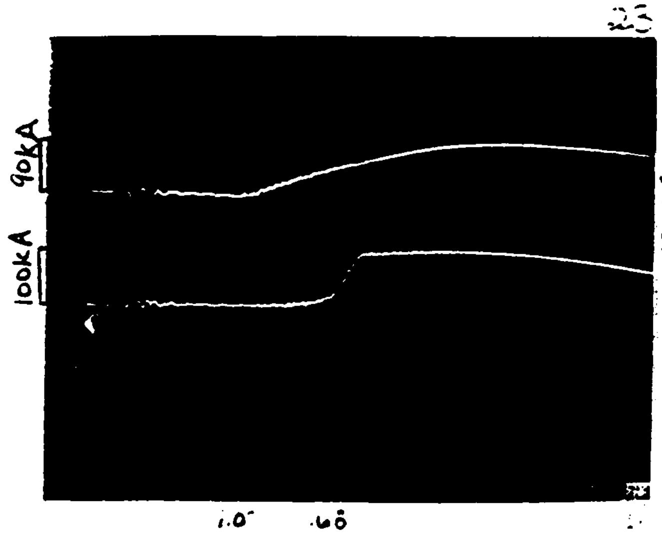
SHOT 21 <u>short circuit load</u>
340 ns conduction time
94 ns opening time
2.9 µs delay

98 kA at capacitor
87 kA upstream
87 kA downstream

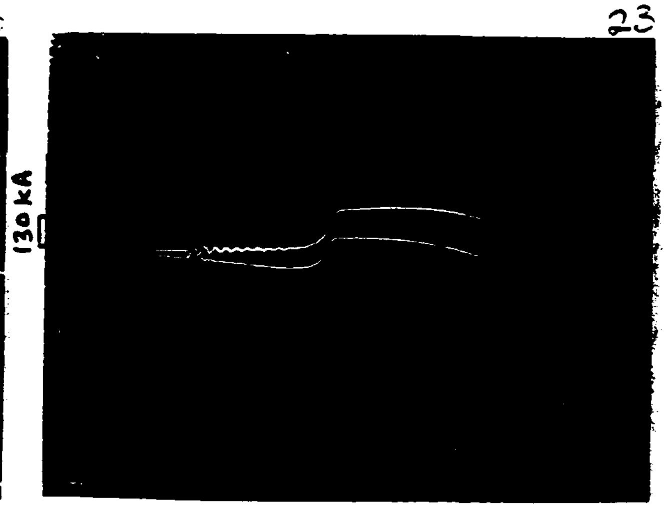


Gun current monitor
Main pulse current monitor
2 µs/div

Switch voltage monitor
Faraday cup -50V bias
.2 µs/div



upstream current monitor
downstream current monitor
.2 µs/div



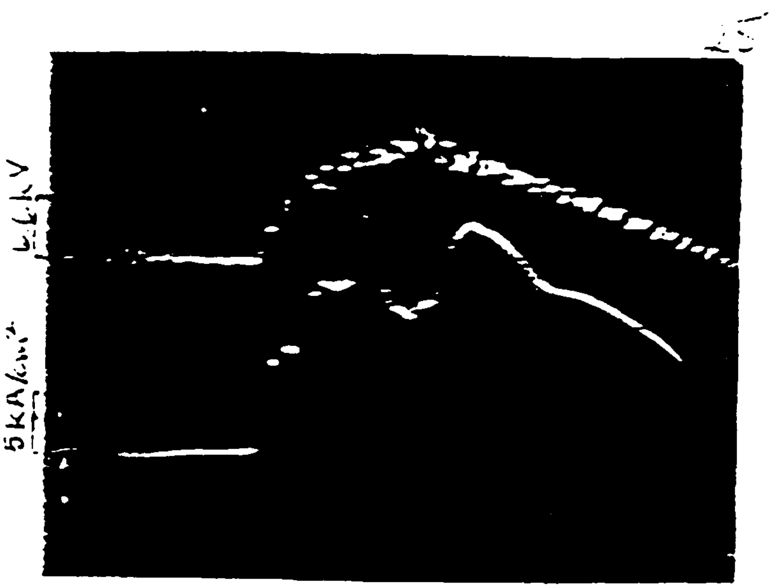
.2µs

further downstream
current monitor
.2 µs/div

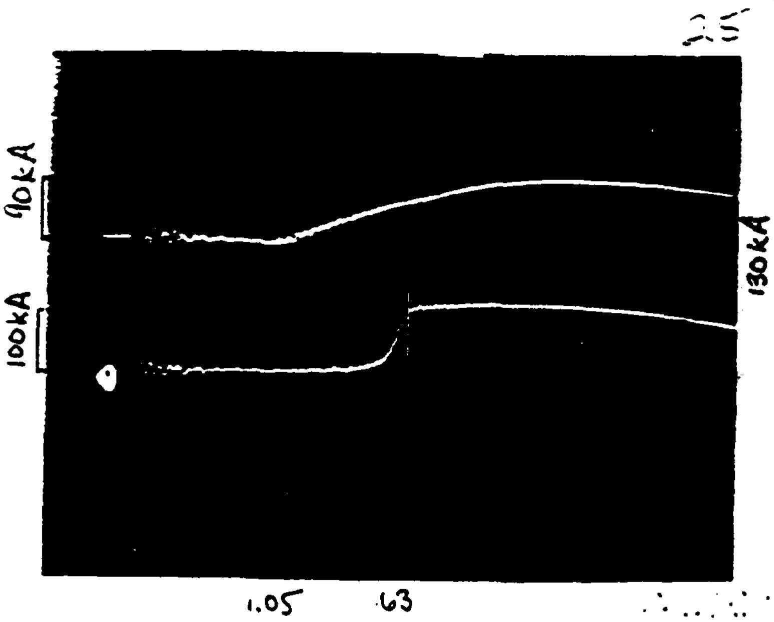
SHOT 23 <u>short circuit load</u>

242 ns conduction time
160 ns opening time
2.9 µs delay

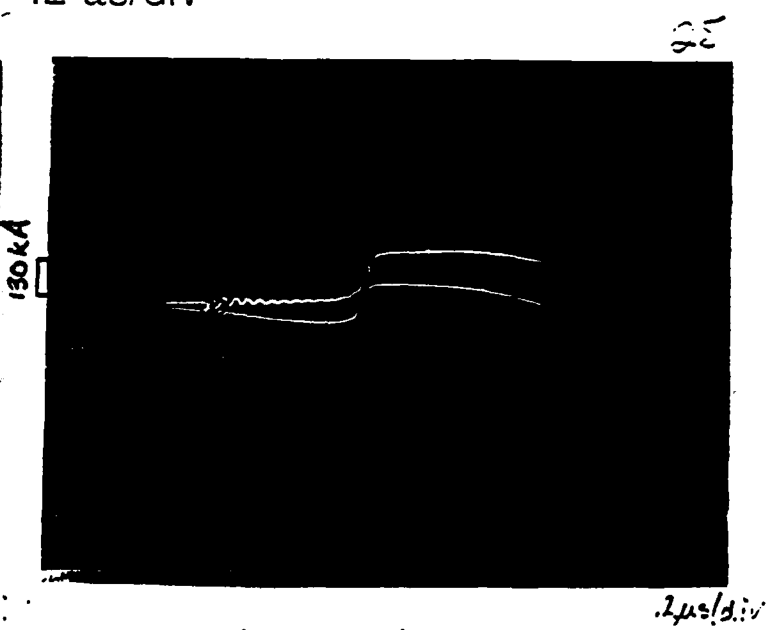
102 kA at capacitor
100 kA upstream
100 kA downstream



Switch voltage monitor
Faraday cup -50V bias
.2 us/div



upstream current monitor
downstream current monitor
.2 µs/div

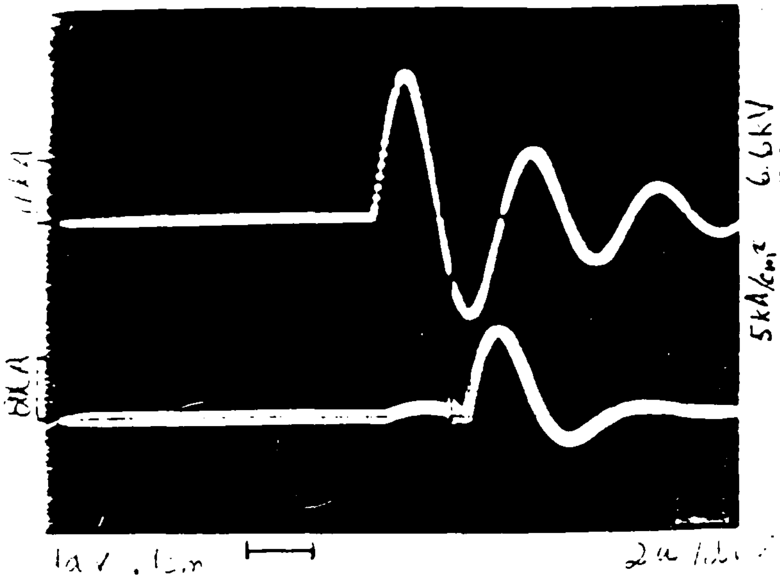


further downstream
current monitor
.2 µs/div

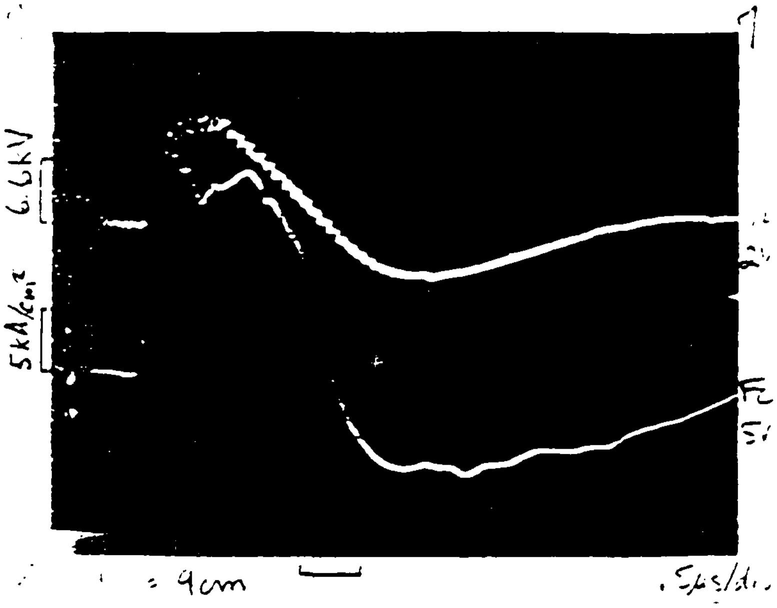
SHOT 25

<u>short circuit load</u>
247 ns conduction time
148 ns opening time
3.0 µs delay

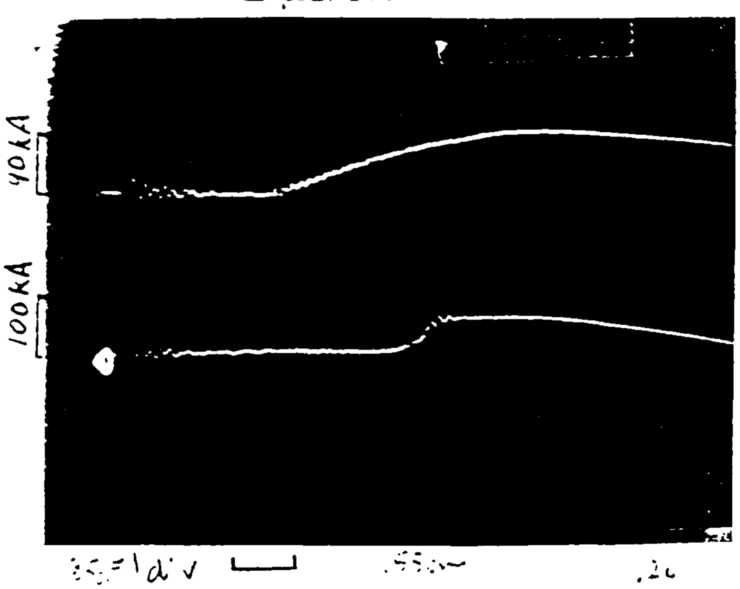
(ground loop problems)
? kA at capacitor
85? kA upstream
118 kA downstream



Gun current monitor
Main pulse current monitor
2 μs/div



Switch voltage monitor
Faraday cup -50V bias
.5 μs div



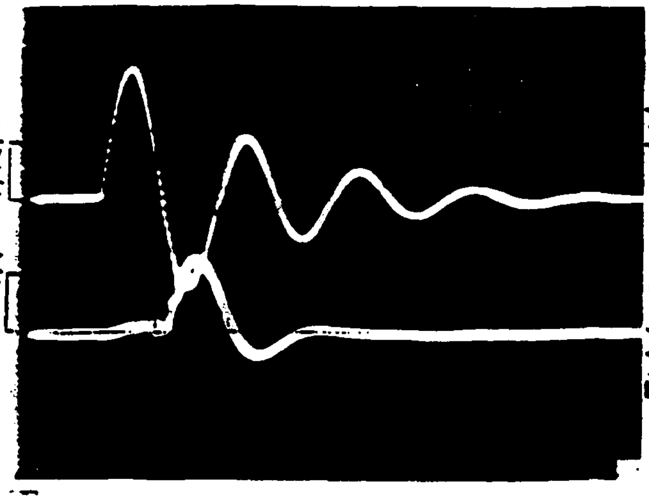
upstream current monitor
downstream current monitor
.2 μs/div

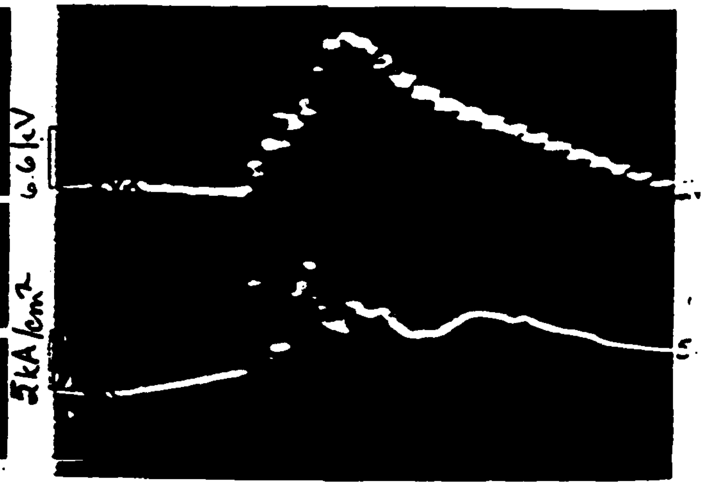
further downstream
current monitor
.2 μs/div

SHOT 7

<u>short circuit load</u>
400 ns conduction time
130 ns opening time
3.2 μs delay

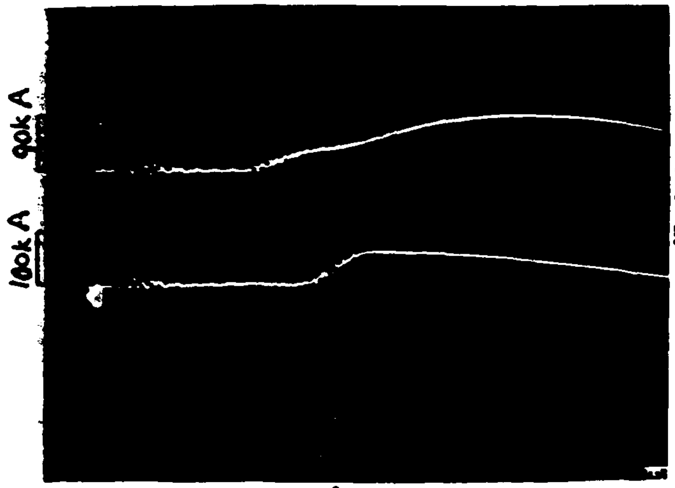
106 kA at capacitor
90 kA upstream
70 kA downstream





Gun current monitor
Main pulse current monitor
2 µs/div

Switch voltage monitor
Faraday cup -50V bias
.2 µs/div



upstream current monitor
downstream current monitor
.2 µs/div

further downstream
current monitor
.2 µs/div

SHOT 42	e-beam diode load 3 mm gap	
	223 ns conduction time	100 kA at capacitor
	188 ns opening time	92 kA upstream
	2.3 µs delay	69 kA downstream

FRAMING PHOTOGRAPHY

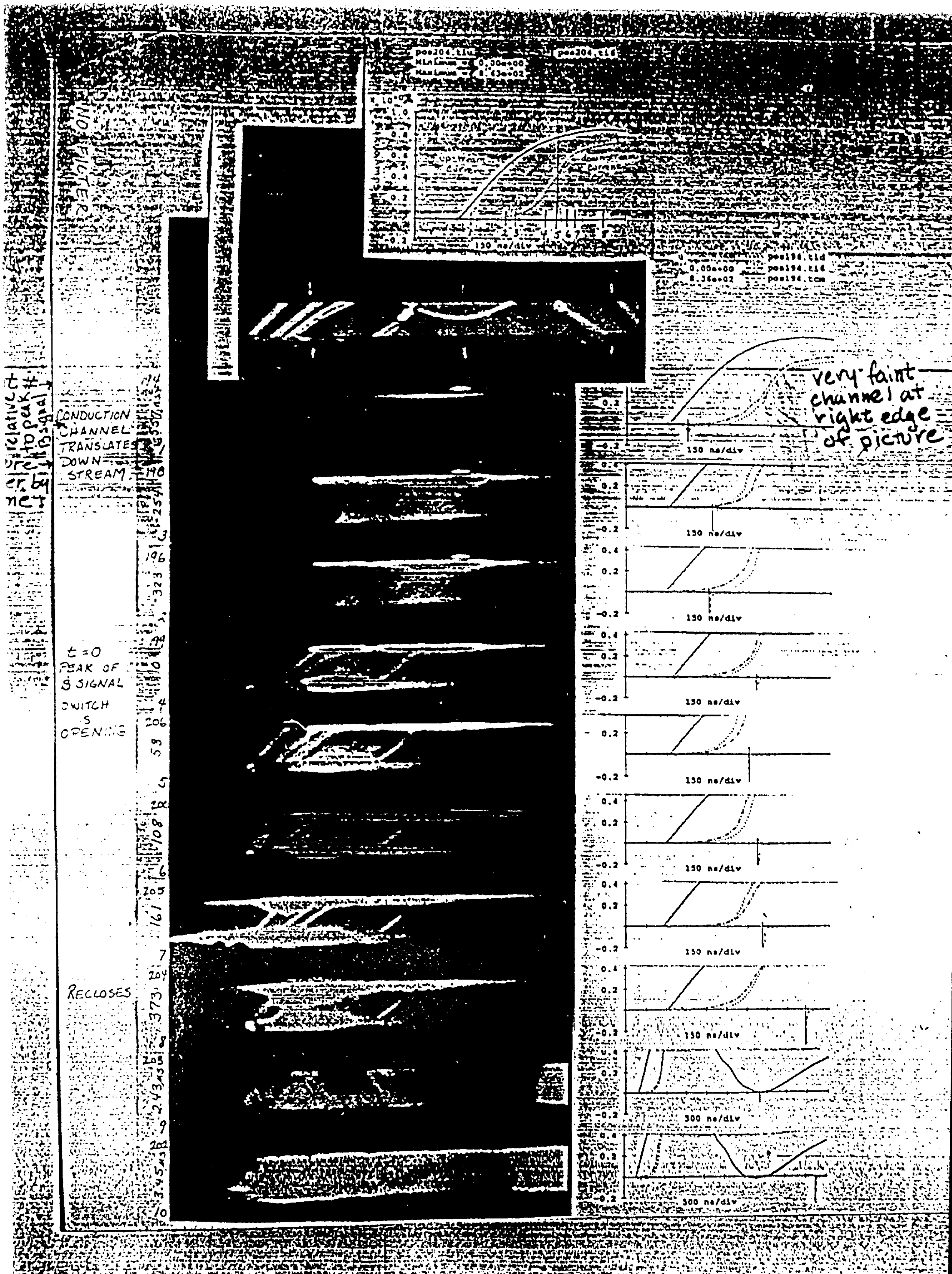
These pictures were taken using a camera put together by our lab engineer Gary Rondeau. It is a microchannel plate fiber optically coupled to a CCD with a maximum gain of 10^4 and a minimum gate time of 5 ns. It is controlled by an IBM PC. Some pictures were taken with all light but most of these are with a narrowband filter that limits the light to the region around 500nm with an 80nm FWHM. This was to cut down on the more intense neutral Carbon lines, although some of the cooler Oxygen and Nitrogen lines are still included. Most of the light is expected to be in doubly and triply ionized Carbon with the filter. All the framing camera shots were with a short circuit load at the same gun current to main current delay.

CONCLUSIONS

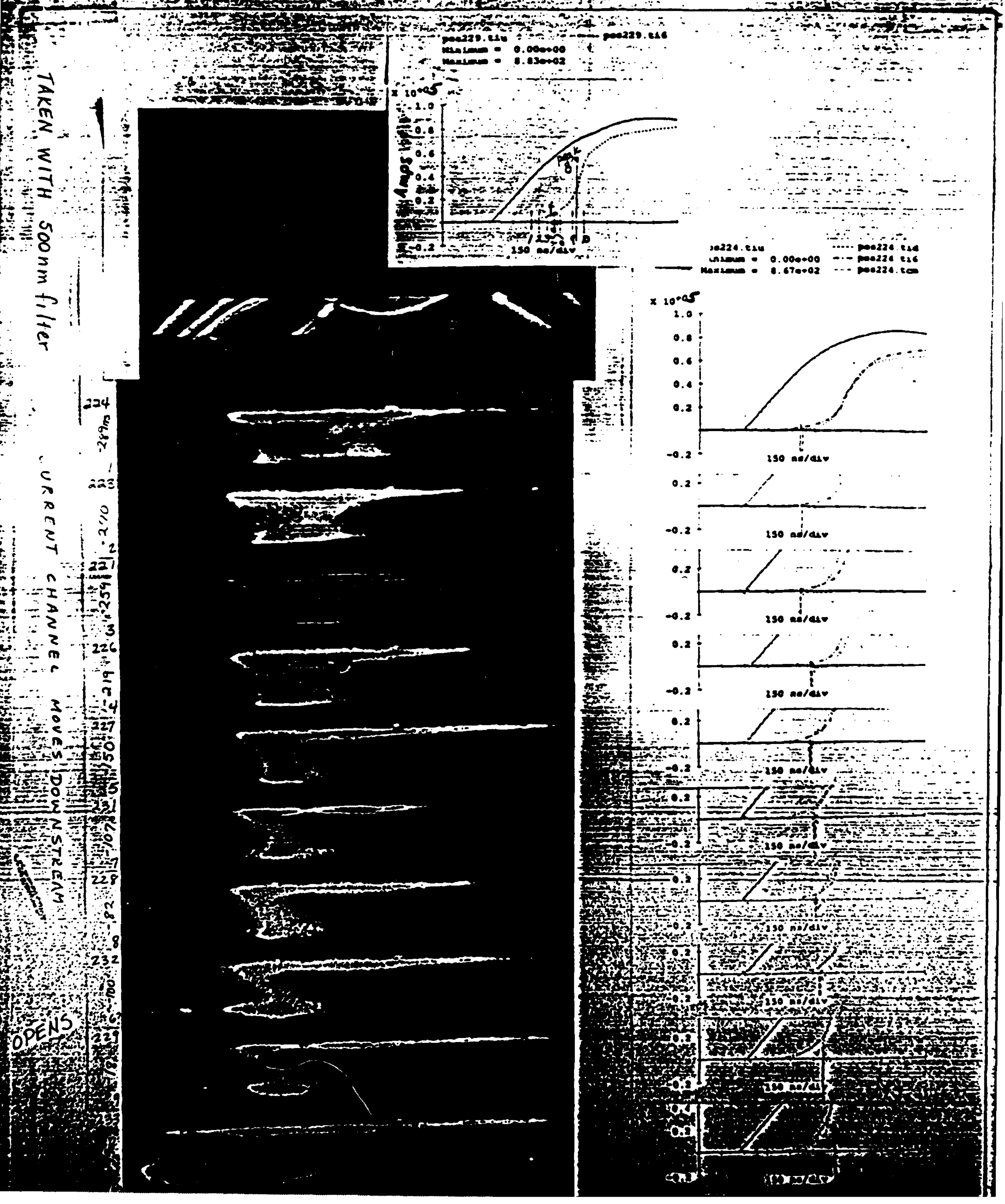
These sequences of framing pictures give an interesting picture of motion in the switch. They look similar in many ways to some of the PIC code results. There is a current channel at an angle to the electrode which propagates downstream and once it hit the downstream end of the switch it has a gap open and some plasma is accelerated down towards the load. Then this switch recloses and the downstream current monitors are fairly constant due to the crowbarred current.

FUTURE WORK

The next step will be to try some more narrowband filters that would eliminate more of the possible Oxygen and Nitrogen lines and just image various charge states of Carbon and possibly Hydrogen. Then relative intensities of various lines and possibly line widths and shifts will be measured to obtain more precise density, temperature and potential information.



NO FILTER
CONDUCTION CHANNEL TRANSLATES DOWN STREAM
t = 0 PEAK OF B SIGNAL
RECLOSES
very faint channel at right edge of picture
150 ns/div
150 ns/div
150 ns/div
150 ns/div
150 ns/div
150 ns/div
150 ns/div
150 ns/div
300 ns/div
300 ns/div



TAKEN WITH 500nm filter
CURRENT CHANNEL MOVES DOWNSTREAM
OPENS
pos229.tiu
Minimum = 0.00e+00
Maximum = 8.83e+02
pos229.ti6
x 10+05
Amps
peak
150 ns/div
Minimum = 0.00e+00
Maximum = 8.67e+02
pos224.tid
pos224.ti6
pos224.tcm
224
223
226
227
231
228
232
229